



Superconducting Magnet Division

Magnet Note

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Title: Construction and Test of the Magnetic Mirror Model of the HTS RIA Quadrupole

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Construction and Test of the Magnetic Mirror Model of the HTS RIA Quadrupole

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The successful construction and test of a magnetic mirror model represents the first significant milestone towards the development of radiation resistant magnets for RIA. This note briefly describes the fabrication and test of this magnet. The maximum achievable field as a function of temperature was studied to help determine the optimum operating temperature in the final design.

Introduction

The first quadrupole triplet in the fragment separator region of RIA will be subjected to several orders of magnitude more radiation and energy deposition than typical beam line and accelerator magnets receive during their entire lifetime [1]. We have developed a super-ferric warm iron design for this magnet [2]. This design significantly reduces the energy deposited in the cold structure and is based on commercially available High Temperature Superconductors (HTS). The magnet will operate at ~ 30 K for efficient removal of the enormous heat (~ 15 kW in the first quadrupole alone). Stainless steel tape is used as a radiation resistant insulation between the turns.

Design

The desired good field aperture in the current design is 280 mm and the maximum operating gradient is 10 T/m. An OPERA3d model of the upper half of the proposed design is shown in Fig. 1. The complete magnet uses 24 HTS coils, each consisting of 175 turns. The coils are enclosed in two cryostats. The design gradient is reached at ~ 125 A. Details of this design are described elsewhere [2].

In response to limited R&D funding, we have developed a magnetic mirror model. This is a cost-effective approach to simulate a similar magnetic and mechanical structure (field gradient, peak fields, Lorentz forces, etc.) but with only one quarter of the conductor. Iron provides a field perpendicular boundary condition at low fields and acts as a mirror if placed at a location where field lines are perpendicular. To further reduce the cost, the coil length has been reduced to 300 mm from 1125 mm in the full-length magnet. The six coils that were built for this magnetic mirror model will become a part of the first short model magnet that requires a total of twenty-four coils. The program was devised so that the initial test could be performed with the existing facilities and without building a special cryostat. An OPERA3d model of this design is shown in Fig. 2.

The magnetic mirror model magnet will address several critical issues prior to proceeding with the more complete R&D program that must be undertaken before such a magnet can be accepted as a critical component of RIA.

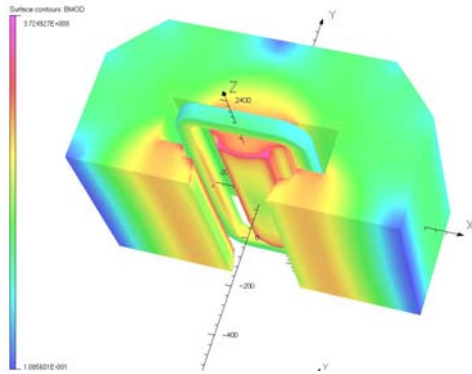


Fig. 1. An OPERA3d model of the 280 mm aperture super-ferrie quadrupole design for RIA. Color indicates the field intensity on the surface of coil and iron regions. The model shows only one symmetric half the complete magnet. The magnet is designed such that two coils create the quadrupole symmetry.

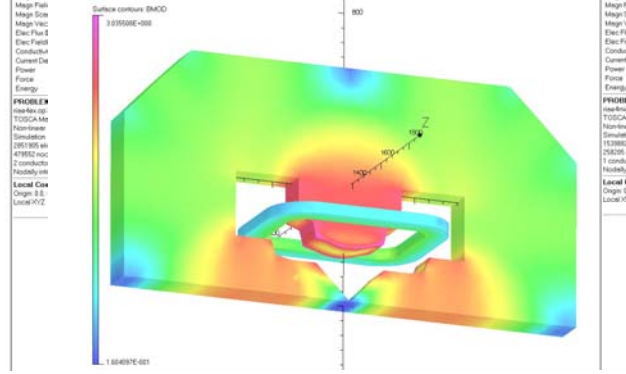


Fig. 2. An OPERA3d model of the magnetic mirror design of magnet. Color indicates the field intensity on the surface of coil and iron regions. Magnetic mirror design uses six coils (instead of twenty-four in normal quad) and the model is made smaller in length to further reduce the cost.

Critical Issues

A few of the critical design issues for HTS based magnets and their operation at an elevated temperature in general, and for the proposed design in particular, are listed below:

- (a) Can a magnet with such a design be made with high temperature superconductor without significant degradation in conductor performance? This is a crucial issue since, unlike the low temperature superconductor (LTS) NbTi, HTS is a brittle material. HTS is prone to degradation and even damage during coil winding and other operations during the manufacturing process. Since no HTS magnet has ever been used in any accelerator or in a beam line, the technology needs to be proven.
- (b) Can the magnet carry the desired current at an elevated operating temperature? The desired operating temperature is in the range of 20 K to 40 K. The final value will depend on the current carrying capacity of the coils and the cost of removing energy at different temperatures.

The magnetic mirror model is designed to address these issues, even though partially, early in the RIA R&D program in a cost-effective manner.

Some of the other critical issues to be addressed in the later part of this program are:

- (a) Is it possible to design the compact cryostat with acceptable heat leak? This work will be carried out in the later part of this year. The measurements of heat leak, simulation of large energy deposition, etc. will be carried out next year.
- (b) What will be the current carrying capacity in a magnetic mirror model with 12 coils and in a full-length magnet with 24 coils? This is a significant issue because even though the magnetic mirror model makes a reasonable simulation of the field in the magnet aperture at lower fields, it only makes a partial simulation of the direction of the field in the coil. In HTS, the current carrying capacity depends significantly on the direction of the field. Moreover, the magnitude of the field (although less critical in determining the current carrying capacity in HTS than in conventional LTS), is also

somewhat different in the magnetic mirror model, a short quadrupole model and a full length RIA quadrupole.

- (c) What is the impact of radiation on the coil? Stainless steel tape is expected to provide a robust insulation against radiation, but one needs to study the radiation tolerance of HTS. A survey of the literature shows that the current carrying capacity initially increases but according to various models, it will decrease when the radiation dose is very large. We will study this effect experimentally next year and iterate the design of the system as and if needed.

Magnet Construction

Fig. 3 and Fig. 4 show the fabrication of HTS coils with two different winding machines. The initial coils were wound using the machine shown in Fig. 3. Now we have adopted the more advanced computer controlled machine shown in Fig. 4. The new winding machine is not only more efficient but also provides better control, automation and recording of various parameters.

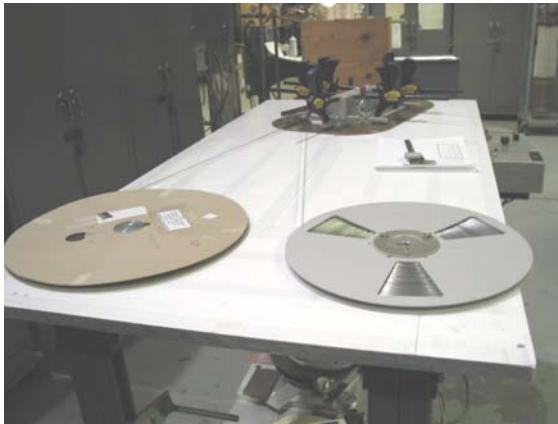


Fig. 3. A coil being made by co-winding HTS tape (on right) and stainless steel insulating tape (left). This is wound using a first generation winding machine that could be quickly set-up.



Fig. 4. A coil being wound with the newer computer controlled winding machine that is more efficient and provides better control, analysis and recording of winding parameters.

A series of photographs (Fig. 5 through Fig. 9) shows other magnet parts and various steps during the construction process. Fig. 5 shows the six coils as three pairs. Fig. 6 shows these coils during their assembly in a support structure. Fig. 7 shows the complete magnetic mirror model magnet. Fig. 8 and Fig. 9 show its preparation for the test.



Fig. 5. Three pairs of coils (six coils) for the magnetic mirror model. These coils are made with HTS tape (nominal 4.2 mm wide and 0.3 mm thick) and insulating stainless steel tape (nominal 4.6 mm wide and 0.04 mm thick).

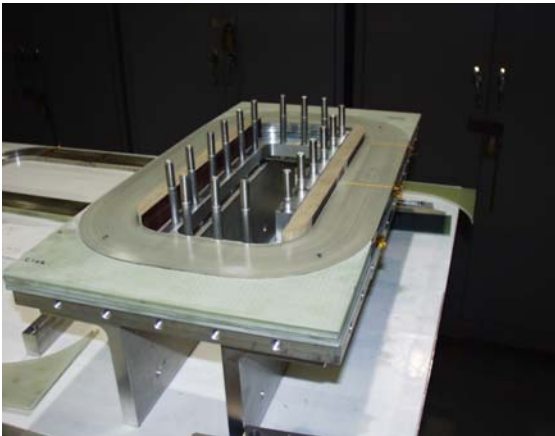


Fig. 6. Three pairs of coils during their assembly a support structure. Four current leads will be brought out so that one can power either all three pairs of coils or any one or two for a variety of test configurations.



Fig. 7. Coils in their support structure and with the pole iron (in the middle, inside the structure), magnetic mirrors (two on the upper side with 45 degree angles on either side of the vertical axis) and iron return yoke.



Fig. 8. Magnetic mirror model magnet, just before the test. The expected operating temperature in RIA will be in the range of 20 K to 40 K, depending on the magnet performance and overall optimization of the system that includes the cost of the large amount of energy removal from the magnet.



Fig. 9. Magnetic mirror model magnet with top hat (top) during its transport to the test station. At the test facility, the magnet can be tested in a wide range of temperature (4.2 K to 80 K).

Test Results

The vertical test facility at BNL is equipped to do various measurements in the temperature range of 4.2 K to 80 K by allowing the magnet to warm adiabatically from 4.2 K. The process is slow enough that the difference in temperature between various sections of coil is small during the measurements. We also installed four temperature sensors to measure the temperature at various places around the structure of the coil. The magnet consists of three pairs of coils. Two additional current leads from either end of the middle coil pair allowed an option where we can power one, two or all three pairs of coils.

In the first set of measurements of the magnetic mirror model, the current carrying capacity of the entire six-coil package was measured as a function of temperature. A summary of these measurements is shown in Fig. 10. The design operating current of RIA quadrupole is ~ 125 A at ~ 30 K. Since in the short magnetic mirror model the peak field on the conductor is somewhat lower than in the full length RIA quadrupole, the equivalent current is about ~ 150 A. The magnet reached the intended current at ~ 30 K with some margin. These measurements were carried out over several days and show that the magnet is robust enough to operate at much higher currents.

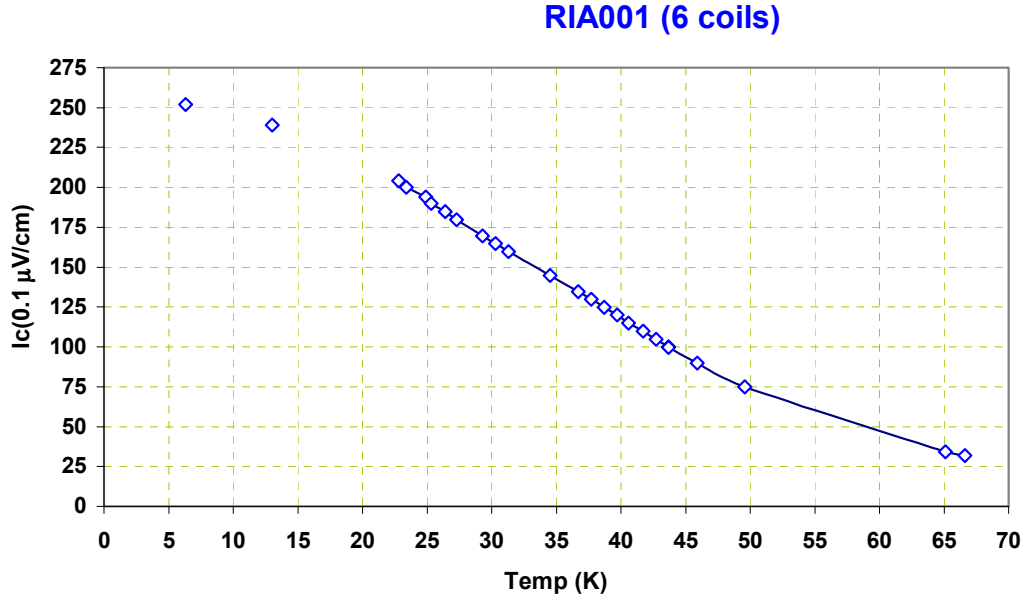


Fig. 10. Critical current as a function of temperature in the first RIA magnetic mirror model. The design operating current of ~ 125 A (at ~ 30 K) in the full-length RIA quadrupole is equivalent to ~ 150 A in the short-length magnetic mirror model due to differences in peak fields in the coils.

For the purpose of these studies we use a voltage drop criterion of $0.1 \mu\text{V/cm}$ or 10^{-9} V/m to define the transition from superconducting state to normal state. This is also a good definition for operating these magnets in the RIA environment. The transition from the superconducting to the normal state is gradual in HTS. This means that a small hotspot will only create heat locally and will not limit the performance of the entire magnet by generating a quench, as would be the case with conventional low temperature

superconductors (LTS). This is a significant advantage of HTS compared to LTS. This is experimentally shown in Fig. 11, where we plot the voltage drop (which indicates resistance) as a function of current.

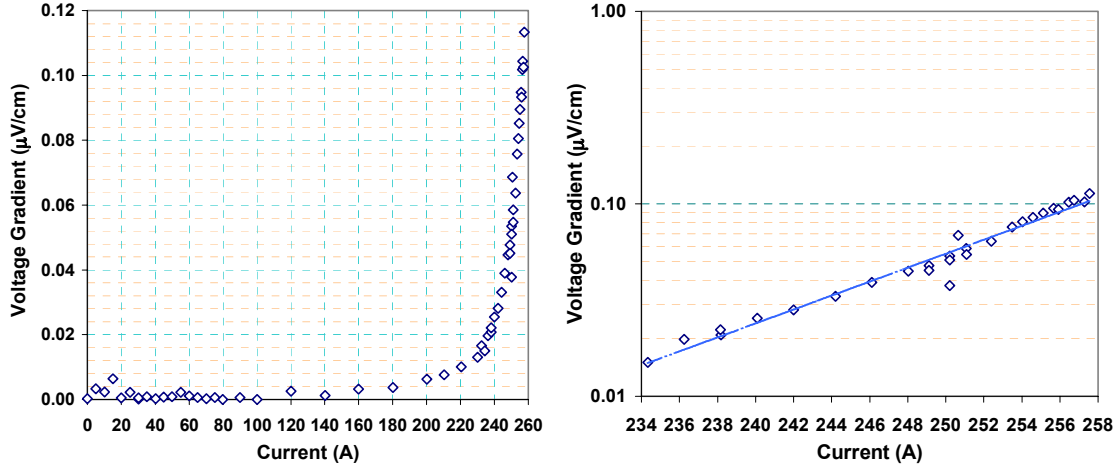


Fig. 11. Voltage Gradient as a function of current at ~ 5 K in RIA magnetic mirror model with six coils. We use a voltage gradient of $0.1 \mu\text{V/cm}$ as a definition of transition from superconducting state to normal state.

Summary and Conclusions

A magnetic mirror model built with commercially available high temperature superconductor has achieved the desired performance (~ 150 A at ~ 30 K). It meets the RIA requirements with some margin. The measured magnet performance is also in line with what was expected from the conductor. Stainless steel tape between the turns has provided the necessary insulation. The successful test of this magnet is the first significant step towards demonstrating that HTS based magnets can provide a good technical solution for one of the most critical items of the RIA proposal.

At present, no accelerator or beam line magnet has been made with HTS. The challenging magnet requirements of the fragment separator region of RIA and the recent advances in HTS offered a unique opportunity to seriously evaluate this solution. The results presented here offers the first proof that, despite its brittle nature, the technology to build magnets with HTS can be developed.

A series of technical issues was identified in a previous section. A program to address those issues in a step-by-step manner has been developed. If successful, this technology will not only offer a good solution to RIA but will also be a major addition to overall accelerator technology.

References:

1. B.M. Sherrill, "Overview of the RIA Project," *Nucl. Instr. Meth. in Phys. Res. B*204 (2003), pp 765-770.
2. R. Gupta, et al., "Radiation Resistant HTS Quadrupole for RIA", Presented at the Applied Superconductivity Conference at Jacksonville, FL, USA (2004).